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NEUTRON IRRADIATION OF Nb_3Sn AND NbTi MULTIFILAMENTARY COMPOSITES*

Don M. Parkin† and A. R. Sweedler♦

ABSTRACT

NbTi and Nb_3Sn multifilamentary composites have been irradiated with fast-neutrons at 60 ± 5°C to fluences of 1.2×10^{20} n/cm^2 (E > 1 MeV). The NbTi samples show only a moderate reduction of I_c as a function of neutron fluence in an applied field of 40 kG. Reductions in I_c were observed for fluences greater than 3×10^{17} n/cm^2 and saturate at 18% for fluences greater than $3\text{-}4\times10^{19}$ n/cm^2. The Nb_3Sn composites showed large neutron radiation induced changes in T_c, I_c and H_{c2}. Reductions in T_c were observed for fluences greater than 7×10^{17} n/cm^2. No measurable changes in I_c(40 kG) were observed below 10^{18} n/cm^2. Between 2 and 3×10^{18} n/cm^2, however, there is an apparent threshold where a very rapid reduction in I_c(40 kG) is initiated. At the threshold the decrease in T_c is 13%. Between the threshold and 1.1×10^{19} n/cm^2, I_c(40 kG) has been reduced to 4% of the unirradiated value. These changes in superconducting properties in NbTi and Nb_3Sn are analysed in terms of the radiation induced defects. The impact of the response to irradiation of both materials on their applications in fusion reactor magnets is discussed.

I. INTRODUCTION

Superconducting magnets have been proposed as integral components of new High Energy Accelerators and Controlled Thermonuclear Reactors (CTR's). Superconducting magnets in both applications will be subject to radiation fields in which the superconductor will undergo radiation damage. The most important of these applications in terms of sustained radiation flux, economics and impact on society is superconducting magnets for plasma confinement in fusion reactors. The large size, 10-20 meter bore for toroidal field coils, and the magnetic field at the plasma, 40 to 60 kG, are important parameters in determining the economics of a fusion reactor concept.[1] As a result, the response of technologically important superconductors to radiation exposure can play an important role in determining the magnet design characteristics and costs of a reactor concept.

The two superconductors most frequently considered for application are NbTi and Nb_3Sn. The maximum field at the conductor for NbTi applications would be 80-90 kG and 150-160 kG for Nb_3Sn. Studies of the effects of radiation using neutrons[2-5] and energetic charged particles[6-10] have shown that changes in I_c, T_c and H_{c2} occur in both materials. Of the two materials, Nb_3Sn which has the A-15 structure, is more sensitive to radiation than NbTi. One specific observation of these studies is that not only are the unirradiated superconducting properties such as critical current a function of sample preparation, but the observed radiation damage effects are also dependent on the initial state of the sample. To study the effects of neutron irradiation in superconducting magnets, engineering materials in the form of multifilamentary composites were used in this study.

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II. EXPERIMENTAL

Samples of NbTi and Nb_3Sn multifilamentary composites and single phase chemical vapor deposited Nb_3Sn were irradiated in the fast-neutron flux of the Brookhaven High Flux Beam Reactor (HFBR). The temperature of the samples during irradiation was 60 ± 5°C. Irradiations were performed up to fluences of 1.2×10^{20} n/cm^2 (E > 1 MeV). The NbTi samples were commercial "Supercon 402" wires with 402 filaments of NbTi and a composite diameter of 0.02 cm. The Nb_3Sn samples were fabricated at Brookhaven National Lab. by M. Suenaga as 0.04 cm wire containing 19 filaments in a Cu-10 wt % Sn matrix. As shown in Fig. 1 the Nb_3Sn filaments consist of a copper core, unreacted Nb layer and a Nb_3Sn diffusion layer. A more detailed description of the sample material is given elsewhere.[11]

Critical current measurements as a function of applied field and measurement temperature were performed using a four-point resistance technique. The critical current was defined as the current for which 3μV was developed across a 1-cm length of sample. Each data point in the figures is the average value obtained from measurements on several independent samples. The critical temperature, T_c, measurements were made using a standard mutual inductance technique.

III. DISCUSSION

NbTi

Results of the 4.2 K measurements of I_c on NbTi as a function of neutron fluence with $H_\perp$=40 kG are given in Fig. 2. Reductions in I_c(40 kG) were observed for fluences greater than 3×10^{17} n/cm^2. At fluences above $3\text{-}4\times10^{19}$ n/cm^2, the reduction in I_c(40 kG) tends to saturate at 18%. For $H_\perp$ less than 40 kG, however, I_c

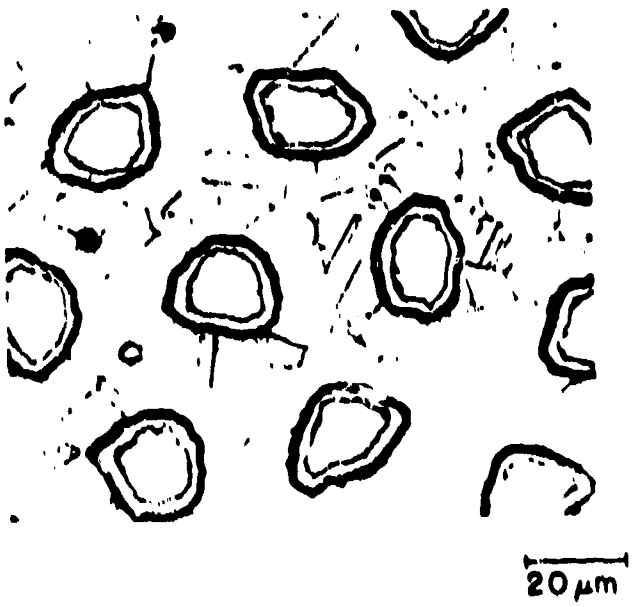

Fig. 1. Photomicrograph of a 19-filament Nb_3Sn composite wire. The central portion of each filament is copper. The unreacted niobium can be seen between the copper core and the darker Nb_3Sn border. The matrix is Cu-10 wt % Sn.

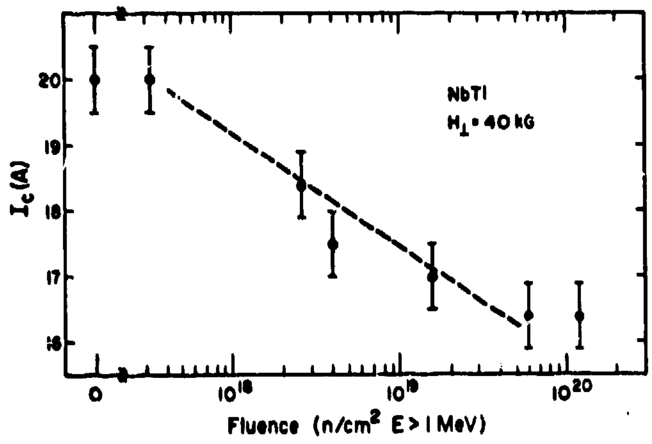

Fig. 2. I_c(40 kG) at 4.2 K as a function of fast-neutron fluence for NbTi multifilamentary composites.

continues to decrease. From 1.6×10^{19} to 1.2×10^{20} n/cm^2 the decrease in I_c at 10 and 20 kG goes from 21 and 17% to 29 and 27% respectively. Further, for $H_\perp$ less than 40 kG, the I_c reductions are not only larger but are observed at lower fluences than at 40 kG.

The magnitude of the reduction in I_c(40 kG) can be compared to other neutron irradiation studies of NbTi filaments. Soell et al.[12] irradiated bare filaments at 5 K with neutrons. After irradiation they annealed their samples at room temperature. After annealing a 15% reduction in I_c remained at a fluence of 7.5×10^{18} n/cm^2. The estimated reduction in I_c from Fig. 2 for this study is 12%.

Decreases in I_c in NbTi have been observed after low temperature neutron irradiation and decreases in I_c, T_c and H_{c2} have been observed after low temperature proton[10] and deuteron[7] irradiation. The general model which these authors have used to analyze the observed reductions in I_c is one in which the radiation induced defects reduce the pinning strength of preexisting pinning centers. The pinning strength is reduced by the decreasing difference in defect concentration between that in the matrix and that in the pinning centers. Wohlleben[7] has extended this analysis to include the effects of reductions in T_c and H_{c2}. He concludes that after low temperature proton irradiation 70% of the decrease in I_c arises from a reduction in pinning strength and 30% from a reduction in T_c or H_{c2}. In the present study only decreases in I_c were measured so that a detailed application of Wohllebens model can not be made. Wohlleben observed a constant percentage degradation of the $I_c(H_\perp, T_m)$ surface for the 3×10^{16} and 1×10^{17} p/cm^2 irradiations and a 7.7% reduction in I_c was found after the 1×10^{17} p/cm^2 irradiation plus room temperature anneal. This data can be compared to the present data by calculating the radiation induced defect production cross section for neutrons and protons. Approximate calculations of the defect production cross sections show that the proton data includes the defect production range 10^{-3} to 5×10^{-3} dpa* and the present neutron data 10^{-4} to 10^{-1} dpa. In the same dpa range the two sets of data show differing radiation effects. In the neutron data, $I_c(H_\perp, T_m)$ is not constant and the corresponding reductions in I_c when compared to the annealed

* dpa is a radiation damage unit which means displacements/atom and is a measure of the number of displacements or interstitial-vacancy pairs produced per lattice atom after a given time integrated flux or fluence.[11]

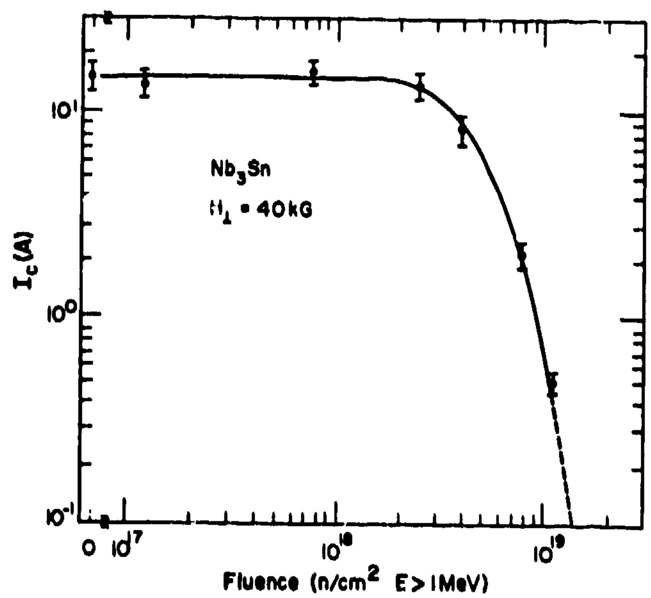

Fig. 3. I_c(40 kG) at 4.2 K as a function of fast-neutron fluence for Nb_3Sn multifilamentary composites.

proton data are larger in the neutron case. These differences could be related to the type of irradiation and the sample material.

Nb_3Sn

Large reductions in T_c, H_{c2} and I_c were observed in Nb_3Sn after neutron irradiation. This sensitivity to irradiation has also been observed by others after neutron[2-5] proton,[6,8,10] deutron[7] and Oxygen[9] bombardment. Little or no reduction in I_c for $H_\perp \leq 40$ kG was observed for neutron fluence below 10^{18} n/cm^2. Between 2 and 3×10^{18} n/cm^2, however, there is an apparent threshold where a very rapid reduction in I_c(40 kG) is initiated as seen in Fig. 3. Between the threshold and 1.1×10^{19} n/cm^2 I_c(40 kG) has been reduced to 4% of the unirradiated value.

The response of T_c to neutron irradiation is shown in Fig. 4. The normalized critical temperature, $T_n = T_c(\phi t)/T_c(0)$ is compared for the Nb_3Sn composite and single phase Nb_3Sn. The initial T_c's are 15 and 18.1 respectively. Measurements of T_c on the Nb_3Sn

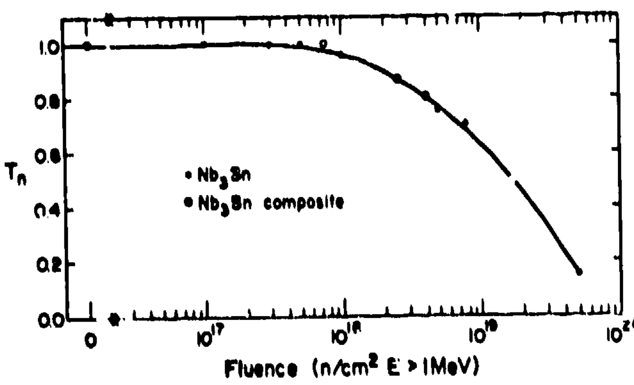

Fig. 4. Normalized critical temperature $T_n = T_c(\phi t)/T_c(0)$ as a function of fast-neutron fluence for Nb_3Sn and Nb_3Sn multifilamentary composites.

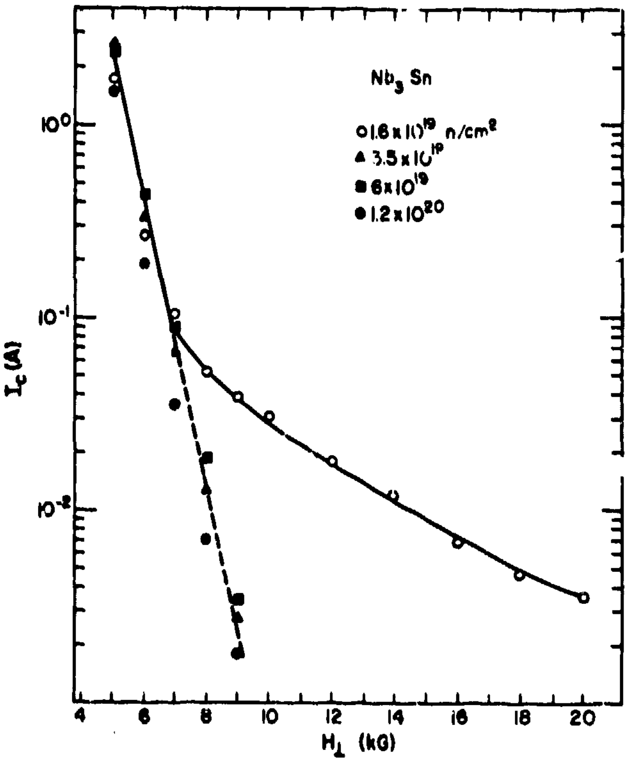

Fig. 5. I_c at 4.2 K as a function of $H_\perp$ for Nb_3Sn multifilamentary composites irradiated with fast-neutrons from 1.6×10^{19} to 1.2×10^{20} n/cm^2.

composite could only be made for T_c greater than 9.1 K, the T_c for the Nb cores in the composite. In this temperature range the normalized reduction in T_c agrees with that for the pure Nb_3Sn. At the current threshold the T_c reduction is 13%.

The magnitude of the radiation induced reductions in $H_{c2}(4.2\ K)$ are indicated in Figs. 1 and 5. Between 1.1×10^{19} and 1.6×10^{19} n/cm^2 $H_{c2}(4.2\ K)$ is reduced below 40 kG. In this fluence range the projected T_c changes from ~ 8.9 to ~ 7.5 K.

Measurements of I_c as a function of $H_\perp$ to 40 kG and measuring temperature, T_m to 1.9 K, were conducted on samples irradiated to fluences greater than 1.6×10^{19} n/cm^2. The results of these measurements are summarized by the data in Fig. 5. Within the data scatter indicated in Fig. 5 no fluence dependence of $I_c(H_\perp,T_m)$ could be detected in these samples. Further the scatter in the data was not a systematic function of fluence. The influence of H_{c2} and T_c on I_c was expected to be measurable since the projected T_c's are from 0-4 K. The results of these measurements can be interpreted in two ways: 1. in the Nb_3Sn composite, the fluence dependence of T_c is greater than for pure Nb_3Sn and T_c was below 1.9 K for all samples, 2. for all T_m and $H_\perp$, $H_{c2}(Nb_3Sn)$ was less than for the Nb cores and $I_c(H_\perp,T_m)$ for Nb_3Sn was much less than for the Nb cores making the Nb_3Sn properties not detectable in the presence of the Nb. It was not possible to determine which interpretation or combination of the two is correct. In either case, the measurements are believed to show the properties of the Nb cores. This intrepretation is supported by the fact that an $H_{c2}(4.2\ K) \approx 9$ kG is in agreement with the value of 9.3 kG reported by Keil et al.[15] for annealed Nb.

Increase followed by decreases in I_c in Nb_3Sn as a function of irradiation fluence have been reported in the literature.[8,9] The basic model used to analyze this data is one in which the radiation induced defects act as pinning centers which enhance the current and after a critical concentration is reached their pinning effectiveness is reduced by further irradiation and the current decreases. The amount of I_c increase being a function of initial I_c value and type of irradiation. In the present results no I_c increase was observed, suggesting that the radiation induced pinning centers were not as effective as the preexisting ones in the composite samples. However, the present data have two important similarities with the literature data. The fluence dependence of the reduction in I_c in the composite samples is similar to the fluence dependence of the decrease in I_c after the peak increase observed by others. This is especially true of the oxygen irradiation data. Second, the point at which I_c starts to decrease in both cases occurs at the same value of dpa, i.e. $\approx 10^{-3}$ dpa. Stated in another way, a rapid decrease in I_c occurs after about the same number of defects have been produced in Nb_3Sn independent of sample preparation or type of irradiation.

At the point where the decrease in I_c occurs, there is a corresponding 13% reduction in T_c. The reduction in T_c following neutron irradiation in Nb_3Sn have been shown to be a general phenomon in a large number of Nb based A-15 superconductors.[16,17] The observed changes in T_c have been correlated with radiation induced disorder in the A-15 structure. When an atom moves through an ordered lattice such as that in Nb_3Sn after receiving kinetic energy from a neutron scattering event, both point defects and lattice disorder are produced as its energy is dissipated.

In Nb_3Sn the superconducting properties are altered both by radiation induced point defects and radiation induced disorder. At the start of the rapid decrease in I_c, the lattice contains not only a sufficient concentration of radiation induced interstitial and vacancy type defects that can directly effect I_c, but also enough radiation induced disorder to produce large reductions in T_c. Both of these types of radiation damage must be considered in analyzing the effect of radiation on I_c in Nb_3Sn. The radiation induced disorder and the resultant changes in T_c and H_{c2} must be incorporated in a model that describes the changes in I_c. The radiation induced change in I_c in Nb_3Sn are due to flux pinning effects and significant changes in the fundamental superconductivity parameters.

IV. CONCLUSIONS

Neutron irradiation at 60 ± 5°C of NbTi multifilamentary composites shows only moderate reductions in I_c(40 kG). Reductions in I_c were observed for fluences greater than 3×10^{17} n/cm^2 and saturation at 18% was observed for fluences above $3\text{-}4\times10^{19}$ n/cm^2. The present neutron irradiation data were compared to other irradiation data. It was observed that the present data agreed with low temperature neutron irradiation data but some differences with low temperature proton data were discussed. The observed reductions in I_c are primarily caused by a radiation induced reduction in pinning strength. Measurements of T_c and H_{c2} were not made so that an analysis of the effects of reductions in T_c and H_{c2} on I_c could not be made.

Large reductions in T_c, H_{c2} and I_c were observed in the Nb_3Sn multifilamentary composites. A very rapid decrease in I_c(40 kG) occurs for neutron fluences greater than $2\text{-}3\times10^{18}$ n/cm^2. Measurable decreases in T_c were observed for fluences greater than 7×10^{17} n/cm^2. Reductions in H_{c2} were also observed. The sensitivity of Nb_3Sn to irradiation is due to radiation induced defects and radiation produced disorder in the A-15 structure.

The operating parameters for superconducting magnets in application in radiation fields such as in a fusion reactor will be at temperatures near 4.2 K and at maximum fields at the conductor of ≈ 160 kG for Nb_3Sn, and 90 kG for NbTi. Since reductions in T_c and H_{c2} have been observed for both NbTi[9] and Nb_3Sn it is reasonable to speculate that the radiation induced degradation of the superconducting properties might be greater and occur at lower fluences than under the conditions discussed in this paper. The relative magnitude of the radiation effects discussed in this paper suggest that Nb_3Sn would be more sensitive to irradiation under these conditions than NbTi.

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